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SUBMITTED TO: 1987 Particle Accelerator Conference, Washington, DC,
March 16-19, 1987

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SIMULATION OF BEAM LOSS IN THE LOS ALAMOS PROTON STORAGE RING*

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Summary

The Los Alamos Proton Storage Ring experiences a significant beam loss as a consequence of scattering in the stripper foil. This paper reviews efforts to understand this loss by computer simulation using the Lie algebraic tracking code MARYLIE, and other special codes that give a very fast simulation of the foil scattering. Simulation results are compared to experimental data.

Introduction

The Proton Storage Ring (PSR) at the Los Alamos Neutron Scattering Center (LANSCE) [1] consists of 10 cells, each containing a 36° bending magnet, and a FODO focusing structure (Fig. 1). A stripper magnet is used to remove the first electron from the 797 MeV H^- beam from the LAMPF linac. The resulting H^0 beam enters the ring through a hole in one of the dipoles, and is then passed through a very thin stripper foil to remove the last electron, leaving a proton beam to be stored in the ring. After an entire 750 μ sec macropulse is collected, which takes 2100 turns around the ring, the extraction kicker is fired, and the stored beam is emptied onto the LANSCE target in 0.25 μ sec to produce an intense pulse of neutrons. A small fraction of the beam is lost in this process, but because of the high design current, this small fraction can cause unacceptable activation of parts of the ring. The losses are much higher than expected for the design aperture, and are clearly related to the scattering in the stripper foil, since they essentially stop when the beam is held off the foil [1]. In some experiments to study the mechanism of these losses, the beam was forced to pass through the foil on every turn (contrary to normal operation), and was stored for up to 10^4 turns. This paper describes some computer simulations carried out in an effort to understand the results of these experiments.

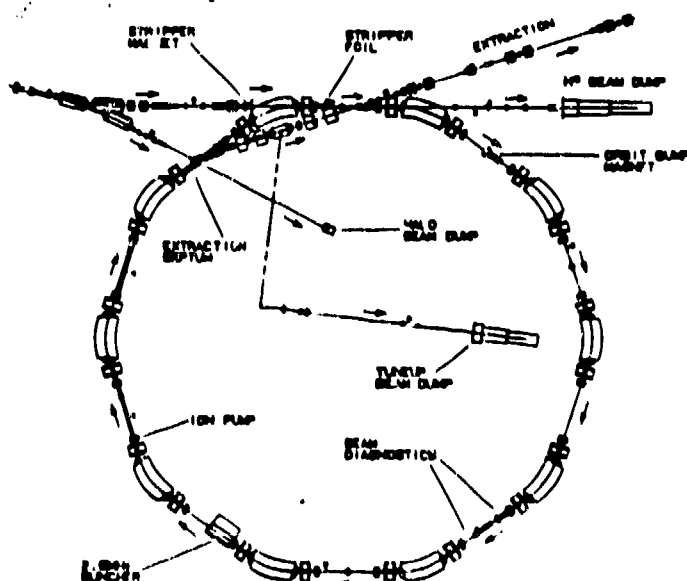


Fig. 1 The Proton Storage Ring. In this drawing the stripper foil is at the top center of sector 0 (12 o'clock position), and the extraction septum is in sector 9 at the 10 o'clock position

Foil Scattering Model

The first task in setting up the simulation is the construction of an accurate, efficient representation of the foil scattering. Tschalär [2] discusses integral representations of the general multiple scattering formalism, as well as the special case of screened Rutherford scattering, for which the single scattering cross-section may be written as

$$\frac{\partial \sigma}{\partial \theta} = \frac{8\pi}{k^2} \left(\frac{Z\alpha}{\beta} \right)^2 \frac{\theta}{(\theta_a^2 + \theta^2)^2} \quad (1)$$

The minimum angle θ_a is determined by electron screening of the nuclear charge, and is estimated by Jackson [3] as $\theta_a = 1/ka$, where the beam momentum is $p = \hbar k$, and $a = 7.06 \times 10^{-9} Z^{-1/3}$ cm for a Thomas-Fermi model of the atom. The maximum scattering angle is determined by the finite nuclear size as $\theta_R = 1/kR$, where $R = 1.4 \times 10^{-13} A^{1/3}$ cm is the nuclear radius. This formula for screened Coulomb scattering was used in a Monte Carlo technique due to H. A. Thiessen [4] to evaluate the net multiple scattering in the stripper foil. The differential cross section given by Eq. 1 is readily integrated to give the total cross section for angles less than a specified polar scattering angle θ :

$$\sigma(\theta) = 4\pi a^2 \left(\frac{Z\alpha}{\beta} \right)^2 \frac{\theta^2}{\theta_a^2 + \theta^2} \quad (2)$$

A set of polar scattering angles consistent with this distribution may be constructed by choosing a random number x between 0 and 1, and solving $\sigma(\theta) = x\sigma(\theta_R)$ for the angle θ that encloses the fraction x of the total cross section:

$$\theta = \theta_a \sqrt{\frac{x}{1 + \left(\frac{\theta_R}{\theta_a}\right)^2 - x}} \quad (3)$$

The azimuthal angle of the scattering is also chosen randomly. The net scattering is then the vector sum of a sequence of such single scatterings as the particle works its way through the foil. The mean free path is determined from the density of scatterers and the total cross section $\sigma(\theta_R)$. About 8 or 9 scatterings were typically needed for one passage through the $300 \mu\text{g}/\text{cm}^2$ carbon foil used in the simulations reported here. To obtain the distribution of polar scattering angles for this foil, some 10^7 particles were subjected to this Monte Carlo process, and the results collected in a 100 bin histogram covering angles from 0 to $1000 \mu\text{r}$. Half the particles were scattered less than $15 \mu\text{r}$, and 90% less than $35 \mu\text{r}$. Despite the large number of particles used, the tail of the histogram was sparsely populated, and was smoothed by fitting with a power law: $f(\theta) = C \times \theta^{-3.45}$. The resulting distribution was integrated and interpolated to construct a 1000 element lookup table containing this distribution of angles: 800 of the entries were less than $15 \mu\text{r}$, 900 were less than $35 \mu\text{r}$, etc. In the subsequent tracking studies, a very fast representation of the foil scattering was obtained by simply choosing polar scattering angles at random from this lookup table.

Fast Linear Numerical Simulations

The basic experimental fact is that when the stored beam passes through the stripper foil on every turn, it decays with a lifetime dependent on the foil thickness. With a $300 \mu\text{g}/\text{cm}^2$

* Work supported by the U.S. Department of Energy.

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foil in the ring, the beam survival fraction at turn n is well fit by the phenomenological formula

$$f(n) = \exp - \left(\frac{n}{n_0} \right)^{1.7} \quad (4)$$

where the lifetime $n_0 = 6010$ turns. From the activation of the machine, it appears the major losses are occurring at the extraction septum, which is 40 mm from the design orbit, and is the smallest known aperture (relative to β_x) in the ring. The obvious hypothesis is that the foil scattering is causing a diffusive growth in the beam size, with the result that the edge of the beam is being scraped off by the septum.

For a preliminary survey of the interaction of ring beam dynamics, foil scattering, and loss on the extraction septum, a very simple linear simulation code (PSIM) was written. The initial transverse phase space coordinates x, p_x, y, p_y at the foil of a set of particles representing the beam is read in from an external file. The input particle set is generated using the parameterization

$$x = \sqrt{r_1 \epsilon_x} \cos \phi_x \quad (5a)$$

$$p_x = \sqrt{\frac{r_1 \epsilon_x}{\beta_x}} \left(\sin \phi_x + \frac{\beta_x'}{2} \cos \phi_x \right) \quad (5b)$$

where $\phi_x = 2\pi r_2$, r_1 and r_2 are random numbers in the range 0 to 1, and (β_x, β_x') are the machine horizontal beta function and its derivative at the foil. The maximum x amplitude of this distribution is $x_{max} = \sqrt{\epsilon_x \beta_x}$, and is taken as an input parameter for the particle generator. The corresponding formulas are used independently to generate (y, p_y) . In this way, a 1000 particle input data set, representing a matched uniform beam with initial amplitudes $x_{max} = 16$ mm and $y_{max} = 8$ mm, was generated and used in all the PSIM runs. These amplitudes are reasonably close to the experimental beam size.

After the initial phase space coordinates of the beam particles are read into PSIM, the transverse (4D) linear transfer matrix of the ring is used to map them around the ring back to the foil, where any particles that land in the shadow of the septum are flagged as lost, and omitted from subsequent turns around the ring. The position of the septum is taken as an input parameter to the simulation, and its shadow on the foil is determined by the M_{12} and M_{22} elements of the linear transfer matrix between septum and foil. The particles that are not lost receive a random momentum kick determined by drawing a random polar angle from the foil scattering lookup table, and resolving it into momentum increments using a random azimuthal angle. The process is then repeated for as many turns as desired, with the particle coordinates being written out periodically, and the loss counter array being written out at the end of the run.

The code is very fast: the simulations shown here tracked 1000 particles through 12,000 turns, and took from 18 to 34 sec CPU time on a Cray-1. The smooth solid curves in Figure 2 show the beam survival fractions for 4 PSIM simulations with the septum position set at 20, 25, 30, and 40 mm. The dashed curve is the data fit given by Eq.(4), and the other two, more ragged, curves are beam survival histograms from nonlinear MARYLIE simulations described in the next section. The main conclusion to be drawn from these linear simulations is that, at least out to 2500 turns, the data is best fit with the septum set at 25 mm, despite the fact that the actual septum is at 40 mm.

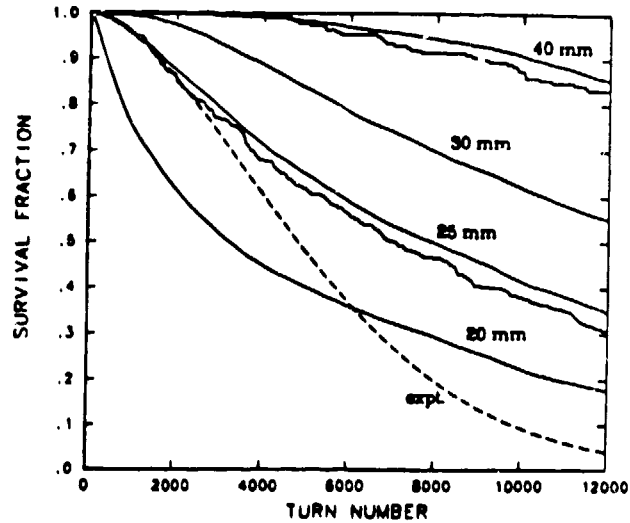


Fig. 2 Beam survival with $300\mu\text{g}/\text{cm}^2$ carbon foil. Simulations with septum locations 20, 25, 30, and 40 mm. Dashed curve is experimental data.

Nonlinear Dynamic Aperture Studies

Since there is no known physical aperture of 25 mm amplitude (full aperture = 50 mm), the question arises as to whether nonlinear effects in the ring could reduce the dynamic aperture this much. The fact that the ring has measured chromaticities of $\xi_x = -1.25$ and $\xi_y = -0.96$, (compared to "natural" chromaticities of -0.82 and -1.3), is taken as evidence for unaccounted sextupole components somewhere in the ring, and also calls for checking nonlinear effects.

The third-order Lie algebraic beam dynamics and analysis code MARYLIE 3.0 [5] is capable of reading in a description of a machine lattice containing up to 3rd order elements (octupoles), and computing the 1st, 2nd, and 3rd order components of the transfer map of the whole machine, or any piece of it, as well as tracking arrays of particles through these maps. It can also adjust the parameters of the lattice elements to meet specified target values for the map and quantities derived from it, such as tunes and chromaticities. The fast lookup table representation of the foil scattering used in PSIM was also put into MARYLIE as a user subroutine. To allow accurate comparison of linear and nonlinear simulations, PSIM reads the linear portion of the transfer map computed by MARYLIE, both codes read the same input particle file, and both write the same form of loss counter file for the subsequent analysis and graphics routines. (MARYLIE can also do the linear simulations, but PSIM is about 200 times faster).

MARYLIE was used in a study of whether a strong sextupole in the ring could reduce its dynamic aperture. An artificial sextupole was introduced into the ring lattice in the form of 10 cm slabs on both ends of the focusing quad just before the septum. The strength S of this sextupole is a variable in these studies, and a value of $S = 17.14\text{T}/\text{m}^2$ yields a horizontal chromaticity of $\xi_x = -1.89$, corresponding to the 1986 measurements.

The input particle sets used were hollow shells in phase space, constructed according to Eq.(5), but with $r_1 = 1$, and the phase ϕ_x taken in 9 equal steps of 40° around the x -ellipse. The maximum amplitude $x_{max} = \sqrt{\epsilon_x \beta_x}$ was the input parameter defining the shell. For each (x, p_x) point in the x -plane, 9 equally spaced points (y, p_y) around the y -ellipse were chosen in the same manner, usually with $y_{max} = x_{max}/2$. These 81 particle phase space shells, with various amplitudes x_{max} , were

tracked through 2000 turns of the PSR model. Loss counters were set whenever a particle being tracked passed outside rectangular aperture limits defined at the septum and at the foil. The output loss counter file is processed into survival fraction histograms for subsequent analysis.

Figure 3 shows the survival fraction histograms for five shells at various amplitudes, with the foil scattering on, and the septum set at 40 mm. The curves are as might be expected for diffusive growth from the initial beam size causing particles to cross the loss threshold. The curves at 28, 32, 34, and 36 mm initial amplitude show that the number of turns until the first loss decreases, and the subsequent loss rate increases, with x_{max} . The prompt initial losses shown by the 40 mm curve are the signature of the initial phase space amplitude crossing the loss threshold, in this case the real septum aperture at 40 mm. The rest of the 40 mm curve presumably represents a normal diffusive loss rate for the particles that survived the initial cut.

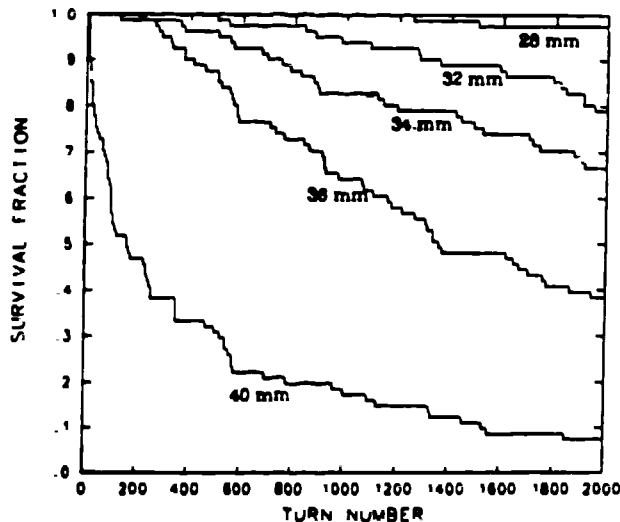


Fig. 3 Survival fraction histograms, with the artificial sextupole turned off, for phase space shells of amplitude 28, 32, 34, 36, and 40 mm at the foil.

Consider now the rather similar looking Figure 4, which shows the fate of the 34 mm shell as the strength S of our artificial sextupole is turned up. The onset of prompt losses occurs between 17 and 25 T/m^2 . This can be taken as an indication that a sextupole strength of about $S = 20 T/m^2$ induces a dynamic aperture of 34 mm, in the sense that some of the particles at that phase space amplitude are suddenly able to migrate rapidly out to the real aperture, and be counted as lost. However, we need a dynamic aperture of 25 mm to match the beam loss data, and a sextupole setting of only $S = 6.6 T/m^2$ to match the present chromaticity data, so we are far from explaining the beam loss data as due to unaccounted sextupole nonlinearities in the ring.

To compare the nonlinear MARYLIE shell calculations to the equivalent full uniform beam linear PSIM simulations, one can interpret the phase space shell survival fraction data as samples of the *a priori* probability of survival out to a given turn, as a function of phase space amplitude. The survival curve for a full beam can then be estimated as the expectation value of the beam amplitude distribution, weighted by this survival probability. This was checked, using a simple trapezoidal rule integration to get the weights, for the linear propagation of a uniform beam through 2000 turns. Good agreement was obtained between this estimate and the result of an actual 1000 particle uniform beam simulation, but the noise due to the skimpy

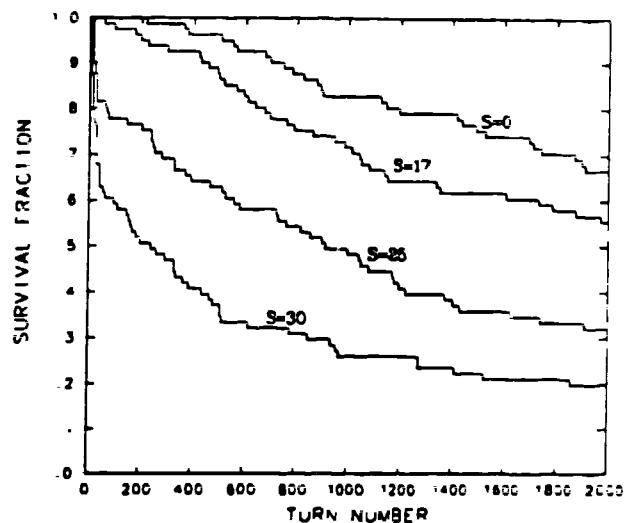


Fig. 4 Survival fraction histograms for the 34 mm phase space shell, with sextupole strength $S = 0, 17, 25$, and $30 T/m^2$.

statistics of the 81 particle shells was still evident. Therefore the final 12000 turn MARYLIE runs, to check the long term losses in the nonlinear model, were done in a straightforward manner using a 400 particle subset of the same uniform beam used in the PSIM runs. To make the PSR model a bit more realistic, the sextupoles were taken as thin lenses attached to both ends of every dipole, as if they were part of its fringe field. The strength of these sextupoles was adjusted to reproduce the measured chromaticities of the ring, with the result 0.03 T/m for the leading sextupole, and 0.19 T/m for the trailing one. The final nonlinear loss histograms for septum positions of 25 and 40 mm are shown in Figure 2.

Conclusions

The conclusion to be drawn from these studies has to be that realistic sextupole nonlinearities in the PSR ring can cause only a slight enhancement of the beam loss rate due to foil scattering, and are nowhere near strong enough to reduce the dynamic aperture sufficiently to agree with the beam loss data. The simulations confirm that normal beam growth due to foil scattering cannot crowd the design aperture. The PSR is essentially linear, and the cause of the anomalous beam loss must be sought elsewhere. This paper should therefore be viewed as a report on work in progress.

Acknowledgments

We wish to acknowledge the very helpful support of A. J. Dragt in the use of MARYLIE, including the modifications needed for these studies. We also wish to acknowledge helpful discussions with R. Macek, H. A. Thelissen, C. Tschalär and T. S. Wang.

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